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An algorithm has been developed to initiate tracks of a ballistic missile in initial exoatmospheric phase, using line of sight measurements from one or more moving platforms.

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ABSTRACT

In this report we deal with the following topics

1. An Interacting Multiple Model Approach for Target Tracking with Glint Noise
2. Ballistic Missile Track Initiation From Satellite Observations
3. Censoring Sensors: A Low-Communication-Rate Scheme for Distributed Detection
4. Adaptive Detection Threshold Optimization for Tracking in Clutter
5. Advanced IR Imaging and Tracking for Hypersonic Intercept
6. A Generalized S-D Assignment Algorithm for Multisensor-Multitarget State Estimation
7. Tracking Maneuvering Targets With Multiple Sensors: Does More Data Always Mean Better Estimates
8. Low Observable Target Motion Analysis Using Amplitude Information
9. Adaptive Beam Pointing Control of a Phased Array Radar in the Presence of ECM and False Alarms Using IMMPDAF
10. MATSurv: Multisensor Air Traffic Surveillance System
11. CW-FM Pulse Fusion Schemes
12. Stabilization of Jump Linear Gaussian Systems Without Mode Observations
13. The Parallelization of a Large-Scale IMM-based Multitarget Tracking Algorithm
14. Theoretical Analysis and Performance Prediction of Tracking in Clutter with Strongest Neighbor Filters
15. IMM Estimation for Multitarget-Multisensor Air Traffic Surveillance
16. Comparison of IMMPDA and IMM-Assignment Algorithms on Real Air Traffic Surveillance Data
17. Multiple-Model Estimation with Variable Structure
18. A Stabilizing Controller for Jump Linear Gaussian Systems with Noisy State Observations
19. Tracking in Clutter With Nearest Neighbor Filters: Analysis and Performance
20. Layered IMM for Tracking Maneuvering Targets in the Presence of Glint
21. Parallelization of a Multiple Model Multitarget Tracking Algorithm with Superlinear Speedups
22. Multitarget Tracking Algorithm Parallelization for Distributed-Memory Computing Systems
23. Waveform Fusion to Improve Tracking
24. Detection of Low SNR Moving Targets with Time Varying Amplitude
25. Bias Compensation and Tracking with Monopulse Radars in the Presence of Multipath
26. Performance Evaluation of Multisensor Track-to-Track Fusion
27. Shared-Memory Parallelization of the Data Association Problem in Multitarget Tracking
28. Multisensor-Multitarget Tracking Algorithm Parallelizations For Air Traffic Surveillance
29. Interacting Multiple Model Methods In Target Tracking: A Survey
30. Image Segmentation Based on Optimal Layering for Precision Tracking
31. Control of Discrete-Time Hybrid Stochastic Systems
32. Heuristic Task Assignment Algorithms Applied to Multisensor-Multitarget Tracking
33. Multitarget Tracking Parallelization for High-Performance Computing Architectures
34. Performability Studies of Automated Manufacturing Systems with Multiple Part Types

0. INTRODUCTION

This report summarizes the results obtained during the period of the Grant. The topics are divided according to the publications generated from the research effort; only items published since 3-1-95 or in press are listed.

1. An Interacting Multiple Model Approach for Target Tracking with Glint Noise

E. Daeipour and Y. Bar-Shalom, *IEEE Transactions on Aerospace and Electronic Systems,* Vol. 31, No. 2, April 1995.

The application of the interacting multiple model (IMM) estimation approach to the problem of target tracking when the measurements are perturbed by glint noise is considered. The IMM is a very effective approach when the system has discrete uncertainties in the dynamic or measurement model as well as continuous uncertainties. It is shown that this method performs better than the "score function" method. It is also shown that the IMM method performs robustly when the exact prior information of the glint noise is not available.

2. Ballistic Missile Track Initiation From Satellite Observations

M. Yeddanapudi, Y. Bar-Shalom, K.R. Pattipati, and S. Deb, *IEEE Transactions on Aerospace and Electronic Systems,* Vol. 31, No. 3, July 1995.

An algorithm is presented to initiate tracks of a ballistic missile in the initial exoatmospheric phase, using line of sight (LOS) measurements from one or more moving platforms (typically satellites). The major feature of this problem is the poor target motion observability which results in a very ill-conditioned estimation problem.

The Gauss-Newton iterative least squares minimization algorithm for estimating the state of a nonlinear deterministic system with nonlinear noisy measurements has been previously applied to the problem of angles-only orbit determination using more than three observations. A major shortcoming of this approach is that convergence of the algorithm depends strongly on the initial guess. By using the more sophisticated Levenberg-Marquardt method in place of the simpler Gauss-Newton algorithm and by developing robust new methods for obtaining the initial guess in both single and multiple satellite scenarios, the above mentioned difficulties have been overcome. In addition, an expression for the Cramer-Rao lower bound (CRLB) on the error covariance matrix of the estimate is derived.

We also incorporate additional partial information as an extra pseudomeasurement and determine a modified maximum likelihood (ML) estimate of the target state and the associated bound on the covariance matrix. In most practical situations, probabilistic models of the target altitude and/or speed at the initial point constitute the most useful additional information.

Monte Carlo simulation studies on some typical scenarios were performed, and the results indicate that the estimation errors are commensurate with the theoretical lower bounds, thus illustrating that the proposed estimators are *efficient*.

3. Censoring Sensors: A Low-Communication-Rate Scheme for Distributed Detection

C. Rago, P. Willett, Y. Bar-Shalom, *IEEE Transactions on Aerospace and Electronic Systems,* Vol. 32, No. 2, April 1996.

We consider a new scheme for distributed detection based on a "censoring" or "send/no-send" idea. The sensors are assumed to "censor" their observations so that each sensor sends to the fusion center only "informative" observations, and leaves those deemed "uninformative" untransmitted.

The main result of this work is that with conditionally independent sensor data and under a communication rate constraint, in order to minimize the probability of error, transmission should occur if and only if the local likelihood ratio value observed by the sensor does *not* fall in a certain single interval. Similar results are derived from Neyman-Pearson and distance-measure viewpoints.

We also discuss simplifications for the most interesting case that the fusion center threshold is high and the communication constraint is severe. We compare censoring with the more common binary-transmission framework and observe its considerable decrease in communication needs. Finally, we explore the use of feedback to achieve optimal performance with very little communication.

4. **Adaptive Detection Threshold Optimization for Tracking in Clutter**
S.B. Gelfand, T.E. Fortmann, Y. Bar-Shalom, *IEEE Transactions on Aerospace and Electronic Systems,* Vol. 32, No. 2, April 1996.

The adaptive optimization of detection thresholds for tracking in clutter is investigated for the probabilistic data association (PDA) filter. Earlier work on this problem involved an approximate steady-state analysis of the state error covariance and is only suitable for time-invariant systems. Furthermore, the method requires numerous assumptions and approximations about the error covariance update equation, and uses a cumbersome graphical optimization algorithm. In this work we propose two adaptive schemes for threshold optimization, namely prior and posterior optimization algorithms which minimize the mean-square state estimation error over detection thresholds which depend on data up to the previous and current time-step, respectively. These algorithms are suitable for real-time implementation in time-varying systems. Some simulation results are presented.

5. **Advanced IR Imaging and Tracking for Hypersonic Intercept**
E. Oron, Y. Bar-Shalom and M. Lachish, *Proc. 1997 IEEE Aerospace Conf.,* Snowmass, CO, Feb. 1997.

This paper presents a method for image processing and IR tracking suitable for an Electro-Optical sensor in a hypersonic missile interceptor. The tracking algorithm is based on both motion and object recognition techniques providing an improved capability of target tracking even in the extreme conditions during the flight of such an interceptor. This method's main features are: 1) SNR improvement in nonuniform noise and background, via spatial kernel filtering, 2) multi-target tracking capability, 3) data association that relies on motion and pattern recognition characteristics of the target, 4) a special method that reduces the image size in order to minimize the computation time without significant loss of accuracy, 5) robust tracking capability of small (distant) targets as well as large (close) targets. Some of the ideas presented in this paper have been successfully implemented in the Arrow ABM program, which has achieved a number of successful MRBM intercepts.

6. **A Generalized S-D Assignment Algorithm for Multisensor-Multitarget State Estimation**
S. Deb, M. Yeddanapudi, K. Pattipati, and Y. Bar-Shalom, *IEEE Transactions on Aerospace and Electronic Systems,* Vol. 33, No. 2, April 1997.

We develop a new algorithm to associate measurements from multiple sensors to identify the *real* targets in a surveillance region, and to estimate their states at any given time. The central problem in a multisensor-multitarget state estimation problem is that of data association - the problem of determining from which target, if any, a particular measurement originated. The data association problem is formulated as a *generalized* S-dimensional (S-D) assignment problem, which is NP-hard for ($S \geq 3$) sensor scans (i.e., measurement lists). We present an efficient and recursive generalized S-D assignment algorithm ($S \geq 3$) employing a successive Lagrangian relaxation technique, with application to the localization of an unknown number of emitters using multiple high frequency direction finder sensors (3, 5, and 7).

7. **Tracking Maneuvering Targets With Multiple Sensors: Does More Data Always Mean Better Estimates?**
W.D. Blair and Y. Bar-Shalom, *IEEE Transactions on Aerospace and Electronic Systems,* Vol. 32, No. 1, January 1996.

When the problem of tracking maneuvering targets with multiple sensors is considered in the literature, the number and type of sensors that support a given target track is usually fixed with respect to a given target location. However, in many multisensor systems, the number and type of sensors supporting a particular target track can vary with time due to the mobility, type, and resource limitations of the individual sensors. This variability in the configuration of the sensor system poses a significant problem when tracking maneuvering targets because of the uncertainty in the target motion model. A Kalman filter is often employed to filter the position measurements for estimating the position, velocity, and acceleration of a target. When designing the Kalman filter, the process noise (acceleration) variance Q is selected such that the 65 to 95% probability region contains the maximum acceleration level of the target. However, when targets maneuver, the acceleration changes in a deterministic manner. Thus, the white noise assumption associated with the process noise is violated and the filter develops a bias in the state estimates during maneuvers. If a larger Q is chosen, the bias in the state estimates is less during a maneuver, but then Q poorly characterizes the target motion when the target is not maneuvering and the filter performance is far from optimal. Here, the problem of tracking maneuvering targets with multiple sensors is illustrated through an example involving target motion in a single coordinate in which it is shown that with two sensors one can have (under certain conditions that include perfect alignment of the sensors) worse track performance than a single sensor. The Interacting Multiple Model (IMM) algorithm is applied to the illustrative example to demonstrate a potential solution to this problem of track filter performance.

8. **Low Observable Target Motion Analysis Using Amplitude Information**
T. Kirubarajan and Y. Bar-Shalom, *IEEE Transactions on Aerospace and Electronic Systems,* Vol. 32, No.4, October 1996.

In conventional passive and active sonar systems, target amplitude information (AI) at the output of the signal processor is used only to declare detections and provide measurements. We show that the AI can be used in passive sonar systems, with or without frequency measurements, in the estimation process itself to enhance the performance in the presence of clutter where the target-originated measurements cannot be identified with certainty, i.e., for "low observable" or "dim" (low signal-to-noise ratio (SNR)) targets. A probabilistic data association (PDA) based maximum likelihood (ML) estimator for target motion analysis (TMA) that uses amplitude information is derived. A track formation algorithm and the Cramer-Rao lower bound (CRLB) *in the presence of false measurements*, which is met by the estimator even under low SNR conditions, are also given. The CRLB is met by the proposed estimator even at 6 dB in a cell (which corresponds to 0 dB for 1 Hz bandwidth in the case of a 0.25 Hz frequency cell) whereas the estimator without AI works only down to 9 dB. Results demonstrate improved accuracy and superior global convergence when compared with the estimator without AI. The same methodology can be used for radar.

9. **Adaptive Beam Pointing Control of a Phased Array Radar in the Presence of ECM and**
T. Kirubarajan, Y. Bar-Shalom, and E. Daeipour, *Proc. 1995 American Control Conference,* Seattle, WA, June 1995.

In this paper, the use of the Interacting Multiple Model (IMM) estimation algorithm combined with the Probabilistic Data Association Filter (PDAF) for adaptive beam pointing control of a phased array radar to track maneuvering targets in the presence of false alarms and Electronic Counter Measures (ECM) is presented. The tracking algorithm includes target track formation and maintenance using IMMPDAF, jammer tracking using an IMM estimator and the adaptive selection of sampling period. Simulation results show the usefulness of using IMMPDAF, in terms of radar energy, average track loss, average dwells and noise reduction.

10. **MATSurv: Multisensor Air Traffic Surveillance System**
M. Yeddanapudi, Y. Bar-Shalom, K. Pattipati, and R. Gassner, *Proceedings of the SPIE Conference on Signal & Data Processing of Small Targets (#2561),* July 1995.

This paper deals with the design and implementation of MATSurv 1 - an experimental Multisensor Air Traffic surveillance system. The proposed system consists of a Kalman filter based state estimator used in conjunction with a two dimensional sliding window assignment algorithm. Real data from two FAA radars is used to evaluate the performance of this algorithm. The results indicate that the proposed algorithm provides a superior classification of the measurements into tracks (i.e., the most likely aircraft trajectories) when compared to the aircraft trajectories obtained using the measurement IDs (squawk or IFF code).

11. **CW-FM Pulse Fusion Schemes**
C. Rago, P. Willett, Y. Bar-Shalom, *Proceedings of the SPIE Conference on Signal & Data Processing of Small Targets (#2561),* July 1995.

It is commonly understood that in active detection systems constant-frequency pulses correspond to good Doppler but poor delay resolution capability; and that linearly-swept frequency pulses have the opposite behavior. Many systems are capable of both types of operation, and hence in this paper the *fusion* of such pulses is examined. It is discovered that in many (but not all) situations the features complement in such a way that tracking performance using a combined CW-FM pulse is improved by an order of magnitude. Also investigated are alternating-pulse systems, and while these are suboptimal their performances appear robust.

12. **Stabilization of Jump Linear Gaussian Systems Without Mode Observations**
G. Pan and Y. Bar-Shalom, *Int. J. Control, 1996,* Vol. 64, N0. 4, 631-661

Systems, such as those subject to abrupt changes (including failure) or those with uncertain dynamic model (or more than one possible model), can be naturally modelled as jump linear (JL) systems. Because of their applications in fields such as tracking, fault-tolerant control, manufacturing process and robots, JL systems have drawn extensive attention. The optimal control and stabilization problem for JL systems, when the mode (system model) is not assumed to be directly and perfectly observed is prohibitive both analytically and computationally because of the dual effect. The main contribution of this work is the sufficient condition for stabilization for a class of adaptive controllers when the mode is not directly observed. We first present the optimal controller under an assumption of a certain type of mode availability. Using this optimal feedback gain, we derive a condition that ensures the stabilizing property for a class of adaptive controllers *without* direct knowledge of the mode. Two specific adaptive controllers (maximum a *posteriori* and averaging) are examined in detail and their stabilizing property is proved. An algorithm to compute the optimal feedback gain and its convergence are presented. Examples show that the performance of the adaptive controllers without mode observations derived here is very close to that of the optimal controller with known modes.

13. **The Parallelization of a Large-Scale IMM-based Multitarget Tracking Algorithm**
R. Popp, K. Pattipati, and Y. Bar-Shalom, *Proceedings of the SPIE Conference on Signal and Data Processing of Small Targets (#2561),* July 1995.

The Interacting Multiple Model (IMM) estimator has been shown to be superior, in terms of tracking accuracy, to a well-tuned Kalman filter when applied to tracking maneuvering targets. However, because of the increasing number of filter modules necessary to cover the possible target maneuvers, the IMM estimator also imposes an additional computational burden. Hence, in an effort to design a real-time IMM-based multitarget tracking algorithm that is *independent* of the number of modules used in the IMM estimator, we propose a "coarse-grained" (dynamic) parallel implementation that is superior, in terms of computational performance, to previous "fine-grained" (static) parallelizations of the IMM estimator. In addition to having the potential of realizing superlinear speedups, the proposed implementation scales to larger multiprocessor systems and is robust. We demonstrate the performance results both analytically and using a measurement database from two FAA air traffic radars.

14. **Theoretical Analysis and Performance Prediction of Tracking in Clutter with Strongest Neighbor Filters**
X. Rong Li and Y. Bar-Shalom, *Proc. 34th IEEE Conference on Decision and Control,* New Orleans, LA, December 1995

A simple and commonly used method for tracking in clutter is the so-called Strongest Neighbor Filter (SNF), which uses the "strongest neighbor" measurement, that is, the one with the strongest intensity (amplitude) in the neighborhood of the predicted target measurement, as if it were the true one. The purpose of this paper is two-fold. First, the following theoretical results of tracking in clutter with SNF are derived: the a priori probabilities of data associated events and the one-step prediction of the matrix mean square error conditioned on these events. Secondly, a technique for prediction without recourse to expensive Monte Carlo simulation of the performance of SNF is presented. This technique can quantify the dynamic process of tracking divergence as well as the steady state performance. The technique is a new development along the line of the recently developed general approach to the performance prediction of algorithms with both continuous and discrete uncertainties.

15. **IMM Estimation for Multitarget-Multisensor Air Traffic Surveillance**
M. Yeddanapudi, Y. Bar-Shalom, and K.R. Pattipati, *Proceedings of the IEEE,* Vol. 85, No. 1, January 1997

This paper deals with the design and implementation of an algorithm for track formation and maintenance in a multisensor Air Traffic Surveillance scenario. The major contribution of the present work is the development of the combined likelihood function that enables the replacement of the Kalman filter (KF) with the much more versatile interacting multiple model (IMM) estimator which, as a self-adjusting variable-bandwidth state estimator, accounts for the various motion modes of the aircraft. This likelihood function defines the objective function used in the measurement to track assignment algorithm. Also, this algorithm incorporates both skin and beacon returns, i.e., it fuses the primary and secondary radar data. Data from two FAA radars are used to evaluate the performance of this algorithm. The use of the IMM estimator yields considerable noise reduction during uniform motion, while maintaining the accuracy of the state estimates during maneuver. Overall, the mean square prediction error (to the next observation time) is reduced by 30% and the rms errors in the altitude rate estimates are reduced by a factor of three over the KF. The usefulness of the tracker presented here is also demonstrated on a noncooperative target.

16. **Comparison of IMMPDA and IMM-Assignment Algorithms on Real Air Traffic Surveillance Data**
T. Kirubarajan, M. Yeddanapudi, Y. Bar-Shalom and K. Pattipati, *Proceedings of the SPIE Conference on Signal and Data Processing of Small Targets (#2759),* Orlando, FL, April 1996

In this paper a comparative performance analysis of the Interacting Multiple Model (IMM) estimation algorithm combined with the Probabilistic Data Association Filter (PDAF) and the IMM-Assignment algorithm for multisensor, multitarget tracking with real air traffic surveillance data is presented. The measurement database from two FAA sensors contains detections of about 75 targets in a wide variety of motion modes. Procedures for track formation/maintenance and data association with IMMPDAF are given. Global performance measures in terms of likelihood ratio and prediction errors are presented. Also, a benchmark track with maneuvers is used to compare the performance of these algorithms for individual tracks.

17. **Multiple-Model Estimation with Variable Structure**
Xiao-Rong Li, and Y. Bar-Shalom, *IEEE Transactions on Automatic Control,* Vol. 41, No. 4, April 1996

Existing multiple-model (MM) estimation algorithms have a fixed structure, i.e., they use a fixed set of models. An important fact that has been overlooked for a long time is how the performance of these algorithms depends on the set of models used. Limitations of the fixed structure algorithms are addressed first. In particular, it is shown theoretically that the use of too many models is performance-wise as bad as that of too few models, apart from the increase in computation. This paper then presents theoretical results pertaining to the two ways of overcoming these limitations: select/construct a better set of models and/or use a variable set of models. This is in contrast to the existing efforts of developing better implementable fixed structure estimators. Both the optimal MM estimator and practical suboptimal algorithms with variable structure are presented. A graph-theoretic formulation of multi-model estimation is also given which leads to a systematic treatment of model-set adaptation and opens up new avenues for the study and design of the MM estimation algorithms. The new approach is illustrated in an example of a nonstationary noise identification problem.

18. **A Stabilizing Controller for Jump Linear Gaussian Systems with Noisy State**

Observations
G. Pan and Y. Bar-Shalom, *European Journal of Control (1996) 2:227-238,* 1996 EUCA

The importance of jump linear systems in modelling practical physical systems, e.g., tracking, repairable systems, systems subject to abrupt changes etc., has drawn extensive attention. Results have been obtained in control, stabilization and filtering, when the mode (system model) is assumed to be directly and perfectly observed, which, in many applications, is an unrealistic assumption. When this is not the case, there have been few methods to find a stabilizing controller when the modes are not observed and the base state is observed only in the presence of noise. A stabilizing controller was recently proposed for the case that the modes are not observed but the base state is perfectly available. In this work, we extend the result to the case that not only the modes are not observed but also the base state is partially measured through a noisy channel. We also show that the stabilizing controller possesses a desirable robustness property with respect to the mode probability transition matrix and the system dynamic model.

The importance of jump linear systems in modelling practical physical systems, e.g., tracking, repairable systems, systems subject to abrupt changes etc., has drawn extensive attention. Results have been obtained in control, stabilization and filtering, when the mode (system model) is assumed to be directly and perfectly observed, which, in many applications, is an unrealistic assumption. When this is not the case, there have been few methods to find a stabilizing controller when the modes are not observed and the base state is observed only in the presence of noise. A stabilizing controller was recently proposed for the case that the modes are not observed but the base state is perfectly available. In this work, we extend the result to the case that not only the modes are not observed but also the base state is partially measured through a noisy channel. We also show that the stabilizing controller possesses a desirable robustness property with respect to the mode probability transition matrix and the system dynamic model.

19. **Tracking in Clutter with Nearest Neighbor Filters: Analysis and Performance**
X. Rong Li and Y. Bar-Shalom, *IEEE Transactions on Aerospace and Electronic Systems,* Vol. 32, No. 3, July, 1996

The measurement that is "closet" to the predicted target measurement is known as the "nearest neighbor" (NN) measurement in tracking. A common method currently in wide use for tracking in clutter is the so-called NN filter, which uses only the NN measurement as if it were the true one. The purpose of this work is twofold. First, the following theoretical results are derived: the a priori probabilities of all three data association events (updates with correct measurement, with incorrect measurement, and no update), the probability density functions (pdfs) of the NN measurement conditioned on the association events, and the one-step-ahead prediction of the matrix mean square error (MSE) conditioned on the association events. Secondly, a technique for prediction *without recourse to expensive Monte Carlo simulations* of the performance of tracking in clutter with the NN filter is presented. It can quantify the dynamic process of tracking divergence as well as the steady-state performance. The technique is a new development along the line of the recently developed general approach to the performance prediction of algorithms with both continuous and discrete uncertainties.

20. **Layered IMM for Tracking Maneuvering Targets in the Presence of Glint**
E. Daeipour and Y. Bar-Shalom, *Proc. 1996 Conference on Information Sciences and Systems,* Princeton, NJ, March 1996

The problem of handling multiple types of discrete uncertainties (modes) in a dynamic system is addressed in this paper. The dynamic model for a target that exhibits maneuvers (one type of discrete uncertainties) and its radar measurements are perturbed by glint noise (another type of discrete uncertainty) is an example of such hybrid system with two mode sets. It is shown how an interacting Multiple Model (IMM) estimator can be designed for such systems. Furthermore, it is shown that by doing the mixing step of the IMM in a number of layered stages, it is possible to achieve some computational savings as compared to the standard IMM. Computer simulations are provided for two examples of maneuvering targets in the presence of glint. The results show that implementation of an IMM via the method described in this paper yields a better performance – in terms of position and velocity Root Mean Square Error – compared to an IMM with nonlinear "score function" based filters.

21. **Parallelization of a Multiple Model Multitarget Tracking Algorithm with Superlinear Speedups**
R.P. Popp, K.R. Pattipati, Y. Bar-Shalom, and M. Yeddanapudi, *IEEE Transactions on Aerospace and Electronics Systems,* 33(1):281-290, January 1997.

The interacting multiple Model (IMM) estimator has been shown to be very effective when applied to air traffic surveillance problems. However, because of the additional filter modules necessary to cover the possible target maneuvers, the IMM estimator also imposes an increasing computational burden. Hence, in an effort to design a real-time multiple model multitarget tracking algorithm that is *independent* of the number of modules used in the state estimator, we propose a "coarse-grained" (dynamic) parallelization that is superior, in terms of computational performance, to a "fine-grained" (static) parallelization of the state estimator, while not sacrificing tracking accuracy. In addition to having the potential of realizing superlinear speedups, the proposed parallelization scales to larger multiprocessor systems and is robust, i.e., it adapts to diverse multitarget scenarios maintaining the same level of efficiency given any one of numerous factors influencing the problem size. We develop and demonstrate the dynamic parallelization on a shared-memory MIMD multiprocessor for a civilian air traffic surveillance problem using a measurement database based on two FAA air traffic control radars.

22. **Multitarget Tracking Algorithm Parallelization for Distributed-Memory Computing Systems**
R.L. Popp, K.R. Pattipati, Y. Bar-Shalom, and R.R. Gassner, *5-th IEEE International Symposium on High-Performance Distributed Computing (HPDC-5),* August 1996

In this paper we present a robust scalable parallelization of a multitarget tracking algorithm developed for air traffic surveillance. We couple the state estimation and data association problems by embedding an Interacting Multiple Model (IMM) state estimator into an optimization-based assignment framework. A SPMD distributed-memory parallelization is described, wherein the interface to the optimization problem, namely, computing the rather numerous gating and IMM state estimates, covariance calculations, and likelihood function evaluations (used as cost coefficients in the assignment problem), is parallelized. We describe several heuristic algorithms developed for the inherent task allocation problem, wherein the problem is one of assigning track tasks, having uncertain processing costs and negligible communication costs, across a set of homogeneous processors to minimize workload imbalances. Using a measurement database based on two FAA air traffic control radars, courtesy of Rome Laboratory, we show that near linear speedups are obtainable on a 32-node Intel Paragon supercomputer using simple task allocation algorithms.

23. **Waveform Fusion to Improve Tracking**
C. Rago, P. Willett, and Y. Bar-Shalom, *Proc. Workshop on Info./Decision Fusion,* Washington, DC, August 1996

It is commonly understood that in radar or active sonar detection systems constant-frequency (CW) pulses correspond to good doppler but poor delay resolution capability; and that linearly-swept frequency (FM) pulses have the opposite behavior. Many systems are capable of both types of operation, and hence in this paper the *fusion* of such pulses is examined from a *system* point of view (i.e. detection-tracking performance). It is shown that tracking errors are highly dependent on the waveform used, and in many situations tracking performance using the optimal waveform is improved by an order of magnitude when compared to a scheme using a single pulse (CW or FM) with the same energy.

24. **Detection of Low SNR Moving Targets with Time Varying Amplitude**
S.M. Tonissen and Y. Bar-Shalom, *Proc. 4th International Symposium on Signal Processing and Applications,* Gold Coast, Australia, August 1996

This paper presents a maximum likelihood solution to the problem of detection and tracking of low SNR constant velocity targets. The signal model improves on previous approaches by accounting for time varying target amplitude. Coupled with a realistic sensor model, this allows for exploitation of signal correlation between resolution cells in the same frame, and also from one frame to the next. Results for the general case and three special cases show good detection performance at SNRs much lower than would be possible with conventional tracking techniques.

25. **Bias Compensation and Tracking with Monopulse Radars in the Presence of Multipath**
E. Daeipour, W.D. Blair, and Y. Bar-Shalom, *IEEE Transactions on Aerospace and Electronic Systems,* Vol. 33, No. 2, April 1997

The problem of tracking targets in the presence of reflections from sea or ground is addressed. Both types of reflections (specular and diffuse) are considered. Specular reflection causes large peak errors followed by an approximately constant bias in the monopulse ratio, while diffuse reflection has random variations which on the average generate a bias in the monopulse ratio. Expressions for the average error (bias) in the monopulse ratio due to specular and diffuse reflections and the corresponding variance in the presence of noise in the radar channels are derived. A maximum maneuver-based filter and a multiple model estimator are used for tracking. Simulation results for five scenarios, typical of sea skimmers, with Swerling III fluctuating radar cross sections indicate the significance and efficiency of the technique developed in this paper – a 65% reduction of the rms error in the target height estimate.

26. **Performance Evaluation of Multisensor Track-to-Track Fusion**
K.C. Chang, R.K. Saha, and Y. Bar-Shalom, *Proc. 1996 IEEE International Symposium on Multisensor Fusion and Integration,* Washington, DC, Dece,ber 1996

Track-to-track fusion is an important part of multisensor fusion. Much research has been done in this area. Chong, et al., among others, presented an optimal fusion formula under an arbitrary communication pattern. This formula is optimal when the underlying systems are deterministic, i.e., the process noise in zero, or when full-rate communication (two sensors exchange information each time they receive new measurements) is employed. However, in practice, the process noise is not negligible due to target maneuvering and sensors typically communicate infrequently to save communication bandwidth. In such situations, the measurements from two sensors are not conditionally (given the previous target state) independent due to the common process noise from the underlying system, and the fusion formula becomes an approximate one. This dependence phenomena was also observed and a formula was derived to compute the cross-covariance of two track estimates obtained by different sensors. Based on these results, a fusion formula was subsequently derived to combine the local estimates which took into account the dependency between the two estimates. Unfortunately, the Bayesian derivation made an assumption that is not met. This paper points out the implicit approximation and shows that the result turns out to be optimal only in the ML (maximum likelihood) sense. A performance evaluation technique is then proposed to study the performance of various track-to-track fusion techniques. The results provide performance bounds of different techniques under various operating conditions which can be used in designing a fusion system.

27. Shared-Memory Parallelization of the Data Association Problem in Multitarget Tracking

R.L. Popp, K.R. Pattipati, Y. Bar-Shalom, and Reda A. Ammar, To appear in *IEEE Trans. Par. And Distri. Systems,* 1997

The focus of this paper is to present the results of our investigation and evaluation of various shared-memory parallelizations of the data association problem in multitarget tracking. The multitarget tracking algorithm developed was for a sparse air traffic surveillance problem and is based on an Interacting Multiple Model (IMM) state estimator embedded into the (2D) assignment framework. The IMM estimator imposes a computational burden in terms of both space and time complexity, since more than one filter model is used to calculate state estimates, covariances, and likelihood functions. In fact, contrary to conventional wisdom, for sparse multitarget tracking problems, we show that the assignment (or data association) problem is *not* the major computational bottlelneck. Instead, the *interface* to the assignment problem, namely computing the rather numerous gating tests and IMM state estimates, covariance calculations, and likelihood function evaluations (used as cost coefficients in the assignment problem), is the major source of the workload. Using a measurement database based on two FAA air traffic control radars, we show that a "coarse-grained" (dynamic) parallelization *across* the numerous tracks found in a multitarget tracking problem is robust, scalable, and demonstrates superior computational performance to previously proposed "fine-grained" (static) parallelizations *within* the IMM.

28. Multisensor-Multitarget Tracking Algorithm Parallelizations for Air Traffic Surveillance

R.L. Popp, K.R. Pattipati, and Y. Bar-Shalom, To appear in *Operations Research,* 1997

To date, there has been a lack of efficient and practical shared- and distributed-memory parallelizations of multisensor-multitarget tracking algorithms for air traffic surveillance. Filling this gap is one of the primary focuses of the present work. We begin by describing our tracking algorithm in terms of an Interacting Multiple Model (IMM) state estimator embedded into an optimization framework, namely, a two-dimensional assignment problem (i.e., weighted bipartite matching). However, contrary to conventional wisdom, the optimization (or data association) problem is *not* the major computational bottleneck; instead, the *interface* to the optimization problem, namely, computing the rather numerous gating tests and IMM state estimates, covariance calculations, and likelihood function evaluations (used as cost coefficients in the assignment problem), is the primary source of the workload. Consequently, with this in mind, we describe a coarse-grained (dynamic) parallelization of the interface to the optimization problem for a general-purpose shared-memory MIMD multiprocessor, where, unlike a fine-grained (static) parallelization, superlinear speedups are realized. In addition, a SPMD distributed-memory parallelization for an Intel paragon high-performance computer is described, where near linear speedups are realized using relatively simple task allocation algorithms. Using a real measurement database based on two FAA air traffic control radars, we show that the parallelizations developed in this work perform well and offer great promise in practice.

29. **Interacting Multiple Model Methods in Target Tracking: A Survey**
E. Mazor, A. Averbuch, Y. Bar-Shalom and J. Dayan, To appear in *IEEE Trans. AES,* January 1998

The Interacting Multiple Model (IMM) estimator is a suboptimal hybrid filter that has been shown to be one of the most cost-effective hybrid state estimation schemes. The main feature of this algorithm is its ability to estimate the state of a dynamic system with several behavior modes which can "switch" from one to another. In particular, the IMM estimator can be a *self-adjusting variable-bandwidth* filter, which makes it natural for tracking maneuvering targets. The importance of this approach is that it is the best compromise available currently between complexity and performance: its computational requirements are nearly linear in the size of the problem (number of models) while its performance is almost the same as that of an algorithm with quadratic complexity.

The objective of this paper is to survey and put in perspective the existing IMM methods for target tracking problems. Special attention is given to the assumptions underlying each algorithm and its applicability to various situations.

30. **Image Segmentation Based on Optimal Layering for Precision Tracking**
A. Kumar, Y. Bar-Shalom, and E. Oron, *DIMACS Series in Discrete Mathematics and Theoretical Computer Science,* Vol. 19, 1995

We present a method for precision tracking of a low observable target based on data obtained from imaging sensors. The image is assumed to consist of gray level intensities in each pixel. The intensity range is divided into a target layer and background layers. A binary image is obtained and grouped into clusters using image segmentation techniques. Using the centroid measurements of the clusters, the Probabilistic Data Association Filter (PDAF) is employed for tracking the centroid of the target.

The boundaries of the target layer are optimized by minimizing the Bayes risk. A closed-form analytical expression is obtained for the single frame based centroid measurement noise variance.

The simulation results presented validate both the expression for the measurement noise variance as well as the performance predictions of the proposed tracking method.

The method is first illustrated on a dim synthetic target occupying about 80 pixels within a 64 x 64 frame in the presence of noise background which can be stronger than the target. The usefulness of the method for practical applications is demonstrated for a highway traffic surveillance problem by considering a sequence of real target images (a moving car) of about 20 pixels in size, in a noisy urban environment.

31. **Control of Discrete-Time Hybrid stochastic Systems**
L. Campo, Y. Bar-Shalom, and X. Rong Li, *Control and Dynamic Systems,* Vol. 76, 1995

An important problem of engineering concern is the control of discrete-time stochastic systems with parameters that may switch among a finite set of values. In this chapter we present the development of a new controller for discrete-time hybrid jump-linear gaussian systems. Here the state and measurement equations have parameter matrices which are functions of a Markov switching process. The jump states are not observed and only the system state is observed in the presence of noise.

This new controller has control gain coefficients that can be generated off-line and is designed to be real-time implementable. It belongs to the open-loop feedback (OLF) class [4] – incorporation of the dual effect would have preluded the above two rather important features. To date, there is no dual (closed-loop) controller for jump-linear stochastic systems with noisy observations.

In addition to presenting a practical control algorithm we also point out an interesting theoretical phenomenon. We show that there is a natural connection between the Interacting Multiple Model (IMM) state estimation algorithm and the control of jump-linear systems. Thus the IMM is the state estimation algorithm of choice for use in these types of control problems.

32. **Heuristic Task Assignment Algorithms Applied to Multisensor-Multitarget Tracking**
R.L. Popp, K.R. Pattipati, and R.G. Gassner, *Proceedings of the SPIE Conference on Signal and Data Processing of Small Targets (#2759-43),* April 1996

In this paper, we are concerned with the problem of assigning track tasks, with uncertain processing costs and negligible communication costs, across a set of homogeneous processors within a distributed computing system to minimize workload imbalances. Since the task processing cost is uncertain at the time of task assignment, we propose several fast heuristic solutions that are extensible, incur very little overhead, and typically react well to changes in the state of the workload. The primary differences between the task assignment algorithms proposed are: (I) the definition of a task assignment cost as a function of past, present, and predicted workload distributions, (ii) whether or not information sharing concerning the state of the workload occurs among processors, and (iii) if workload state information is shared, the reactiveness of the algorithm to such information (i.e., high-pass, moderate, low-pass information filtering). We show, in context of a multisensor-multitarget tracking problem, that using the heuristic task assignment algorithms proposed can yield excellent results and offer great promise in practice.

33. **Multitarget Tracking Parallelization for High-Performance Computing Architectures**
R.L. Popp, K.R. Pattipati, and R.R. Gassner, *Proceedings of the 4th Annual High-Performance Computing Symposium (HPC '96),* April '96

The problem under investigation is the detection and estimation of potentially hundreds of maneuvering airborne targets in "real-time", using line of sight measurements from one or more active sensors. In this paper, we present a robust, parallel algorithm to track the states of such targets for the distributed-memory "message passing" class of parallel computing architectures. Specifically, we embed the Interacting Multiple Model (IMM) estimator into a two-dimensional (2D) assignment-based algorithm to handle both the state estimation and measurement-to-track data association problems. Based on the supervisor/worker paradigm, two parallelizations are described, differing in the track distribution strategies employed. In particular, we show that a "static" mod p (p processors) uniform distribution scheme does not reflect the computational load across the processor set, and hence, degraded performance ensues because of load imbalances. However, a distribution scheme based on a *track age* metric, which is an indicator of the expected workload, indirectly improves performance by "dynamically" balancing the workload across the processor set via a reallocation of tracks. We develop and demonstrate the parallelizations using a measurement database based on two FAA air traffic control radars and a 32-node Intel Paragon high-performance computer (HPC).

34. **Performability Studies of Automated Manufacturing Systems with Multiple Part Types**
N. Viswanadham, K.R. Pattipati, and V. Gopalakrishna, *IEEE Transactions on Robotics and Automation,* Vol. 11, No. 5, October 1995,

In this paper, we consider the transient performance analysis of failure-prone manufacturing systems producing multiple part types. We decompose the exact monolithic model into (a) a slower time scale structure state process modeling the failure and repair and (b) a faster time scale performance model describing the part processing and the material movement. We combine the solution of these two models to show that the accumulated reward over a given time interval is a solution of a set of forward or adjoint multidimensional linear hyperbolic partial differential equations. This result generalizes the existing results on composite performance-dependability analysis of manufacturing systems. We also present efficient numerical methods for computing the distribution of the cumulative operation time, and the mean and variance of the cumulative production over a given time interval. Further, we bring out the significance of these results in the manufacturing systems context through several examples.